17th International Conference on the Applications of Computer
Science and Mathematics in Architecture and Civil Engineering
K. Gürlebeck and C. Könke (eds.)
Weimar, Germany, 12–14 July 2006

VARIATION OF ROTATIONAL RESTRAINT IN GRID DECK CONNECTION DUE TO CORROSION DAMAGE AND STRENGTHENING

W. Siekierski*

* *Poznań University of Technology, Poznań, Poland*
ul. Piotrowo 5, 61-138 Poznań, Poland
E-mail: Wojciech.Siekierski@put.poznan.pl

Keywords: rotational restraint coefficient, bridge deck, connection, finite element method.

Abstract. *Numerical analysis of stringer-to-crossbeam connection is presented. The sensitivity of the rotational restraint coefficient of stringer at the connection to corrosion damage and strengthening is analyzed. Finite element method is employed. FEM model of the connection is presented. It is built with shell elements, modelling webs and flanges, and systems of beam and spring elements modelling rivets. Method of rivet modelling is verified by lab test results. Two criteria of the assessment of rotational restraint coefficient are applied: static and kinematic one. The former is based on bending moment distribution in the considered member, the latter one – on the member rotation at the given joint. The general conclusion is that strengthening critical regions of structural member alters flexural stiffness distribution over member length and influences rotational restraint at its connection to other members. The impact depends on criterion chosen for rotational restraint coefficient assessment.*

1 INTRODUCTION AND MOTIVATION

Engineering computations are being performed usually prior to construction. However, sometimes they are carried out for existing, very old structures. In such cases correct assessment of static parameters, i.e. overall and cross-sectional dimensions, loading, conditions at supports, is necessary.

The problem described here concerns a 100-year old steel road-railway bridge shown in Fig.1. It is a truss girder bridge with a grid deck – see Fig.2. Due to construction of the deck the rain water caused severe corrosion damage to stringers and crossbeams. The in situ investigation revealed 10÷15% decrease of top flange thickness. Strengthening of the mentioned members became necessary.

Fig.1. General view of the bridge concerned

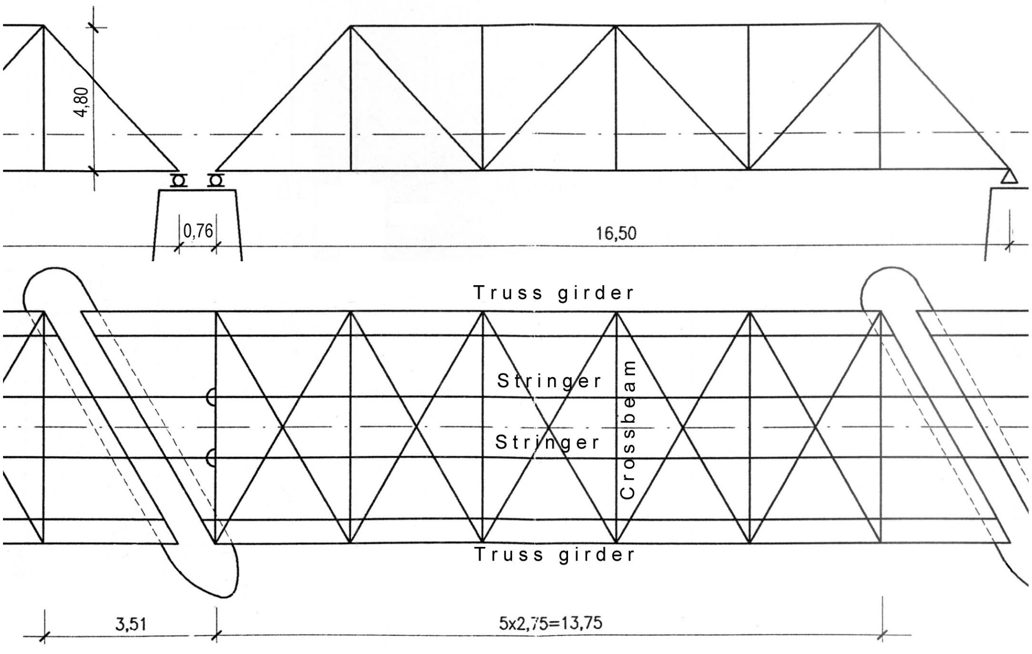

Fig.2. Scheme of truss girder and bridge deck

Numerical analysis was carried out to assess sensitivity of rotational restraint coefficient of stringer-to-crossbeam connection to corrosion damage and planned method of strengthening.

2 ANALYZED CONNECTION

Initial connection layout is presented in Fig.3.

a) b)

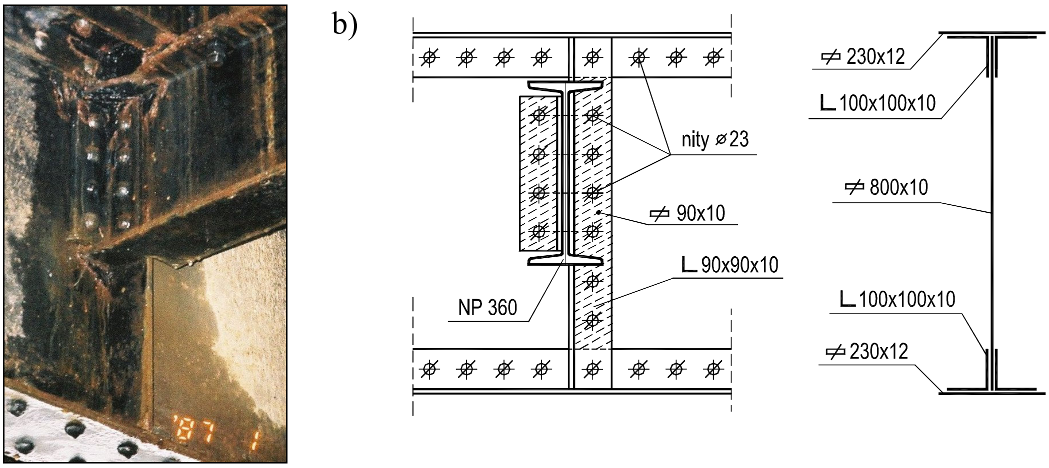

Fig.3. Analyzed connection: a) general view, b) initial layout and crossbeam cross-section

The hot-rolled I360 beam (stringer) is connected to 824mm high, riveted I-girder (crossbeam). The joint itself consists of pair of angles riveted only to webs of both beams – see Fig.3. Rivets of ϕ23 are used. The connection lacks typical elements that are to provide structural continuity of stringers "over" crossbeams. Nonetheless one of angles in each pair extends from top to bottom flange of crossbeam and it is connected to them with single rivets.

Due to corrosion damage of deck strengthening of structural members became necessary. The strengthening systems for stringer and crossbeam, presented in Fig.4, are similar: flat bars and angles on the both sides of web, near top flange.

a)

b)

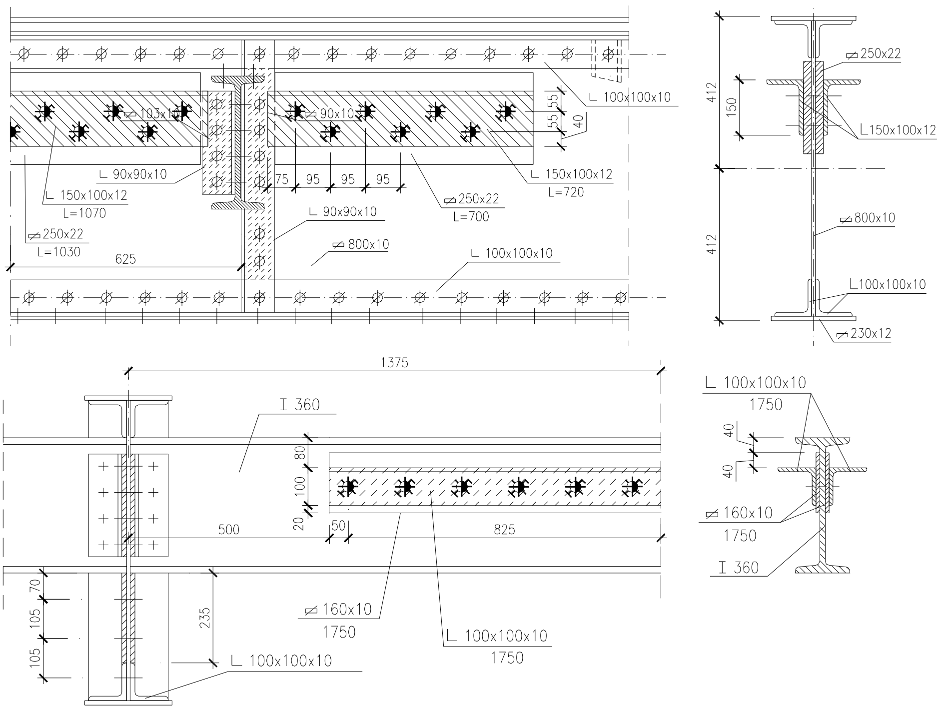

Fig.4. Layout of strengthening: a) crossbeam, b) stringer

3 FINITE ELEMENT MODELLING

3.1 Rivet modelling

Inappropriate modelling of connectors such as bolts and rivets may lead to wrong assessment of rotational restraint of a structural member in question at given connection. From this point of view complex 3D modelling is preferable. However, it may turn out to be inefficient, especially when some necessary material and structural data are unavailable.

It is possible to apply simplified modelling that will regard crucial characteristics of actual structure, cutting down time and money expenditure. Such approach was chosen for the problem in question.

Each of rivets is modelled with system of beam and spring elements – see Fig.5. This way of rivet modelling is compatible with approach to structural member modelling with shell elements that is described in detail in chapter 3.3. Application of brick elements to model rivets, as in [1], implies such modelling of structural members.

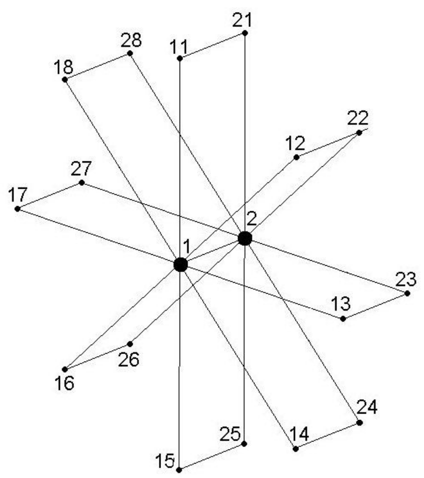

Fig.5. System of elements modelling a rivet

Fig.5 shows an example of element system used to model a rivet. It connects two steel sheets, located in planes set by nodes 11÷18 and 21÷28. The nodes are located in corners of regular octagons – approximation of holes in the sheets. In each of connected sheet planes there are 8 spring elements oriented radially (elements [11–1]÷[18–1] and [21–2]÷[28–2] in Fig.5). They connect nodes 11÷18 and 21÷28 (that belong to shell elements modelling connected steel sheets), located along hole perimeter, to respective nodes 1 and 2, located on rivet axis. Beam elements are located along rivet axis (element [1–2]) and along its perimeter surface (elements [11–21], [12–22],…, [18–28]). Forces between rivet and steel sheets are assumed to be transferred at the nodes located along shank perimeter in steel sheet plane – that is, in the case of presented example, nodes: 11÷18 and 21÷28.

Spring elements and beam elements located on rivet axis are meant to carry shear, while beam elements located along rivet perimeter surface – tension. This principle governs the rivet stiffness division into beam elements:
– perimeter beam elements represent rivet axial stiffness,
– beam element in the centre respects rivet flexural and torsional stiffness.

Behaviour of spring elements is characterized by variation of spring length as a function of force transferred by the spring (in the spring direction). The relationship is assumed to be nonlinear, different for compression and tension. In compression rivet diameter and thickness of given steel sheet is regarded, while in tension transferred force drops to “zero”.

3.2 Verification of rivet modelling

The proposed method of rivet modelling was used in the FEM model of experimental test of T-stub connection described in [2]. In this test the connection presented in Fig.6a was subjected to tensile force acting in the web direction. Variation of distance *d* as function of the force *P*, was recorded.

The aim of the verification was to find whether the applied modelling is capable of recreating connection stiffness within elastic range. That is why existence of non-preloaded bolts instead of rivets was of minor importance.

The stiffness of T-stub connection in the test relies mainly on bolts. Moreover, method of force transfer in the tested connection is similar to the case of investigated bridge deck connection.

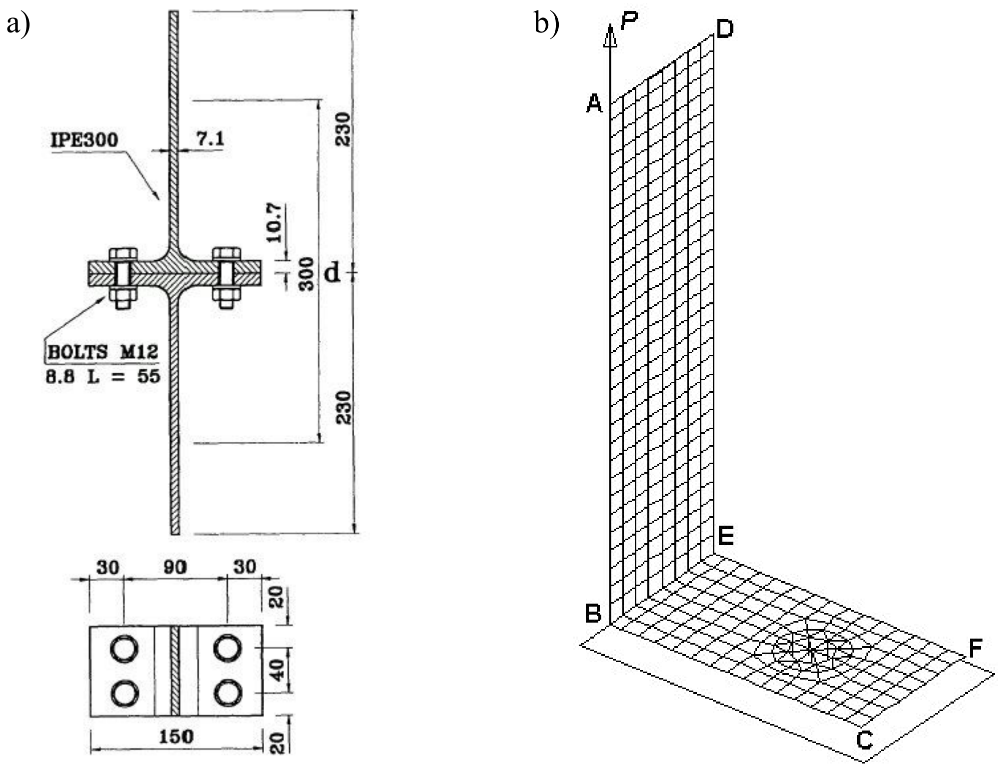

Fig.6. Rivet modelling verification: a) tested T-stub connection (figure after [2]), b) FEM mesh

A quarter of one of the T-stubs was modelled. Boundary conditions due to symmetry were applied on the surface ABED and along the edge ABC as well as at free ends of beam elements modelling the bolt shank. Flange and web were modelled with 4- and 3-node elements of 6 degrees of freedom per node. Interaction with the opposite flange was modelled as non-friction contact with rigid surface, located in the symmetry plane, marked in Fig.6.

Since shell elements modelling flange are located in its symmetry plane, length of beam elements modelling the bolt shank is smaller than the actual length of bolt shank. This is accounted for in combination with Agerskov's model [3] of bolt. Equivalent bolt area of the bolt present in the FEM model, that respects effective length of actual bolt, is calculated from the following equation:

$$\frac{E\cdot A_b}{\left(l_s+1{,}43\cdot l_t+0{,}71\cdot l_n\right)+2\cdot\left(0{,}1\cdot l_n+0.2\cdot l_w\right)}=\frac{E\cdot A_{equiv}}{L_{model}} \tag{1}$$

where: E is steel Young modulus, A_b indicates bolt gross cross-section, l_s, l_t, l_n are parameters that can be obtained from bolt geometry, shown in Fig.7, A_{equiv} and L_{model} are equivalent bolt area in the FEM model and bolt shank length present in the FEM model, respectively.

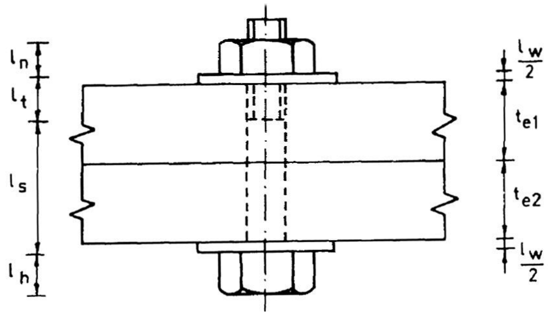

Fig.7. Bolt geometry (figure after [2]); for the M12 bolt ls=0,025m

Material data was taken after [2]. Elastic behaviour and small strain were assumed.

Recorded variation of distance "d" as function of the force *P* within elastic range was equal approximately 8,0 mm/MN, while from FEM analysis: 7,6 mm/MN. The small (about 5%) error justifies application of presented method of rivet modelling to assessment of rotational restrained of stringer-to-crossbeam connection.

All FEM computations described in this paper were carried out using Abaqus package [4], installed at Poznań Supercomputing and Networking Centre.

3.3 Grid deck connection modelling

FEM computational models of grid deck connection are shown in Fig.8. The models consist of half of stringer span, half of crossbeam, connecting angles and strengthening members – overlays and angles – see Fig.8.

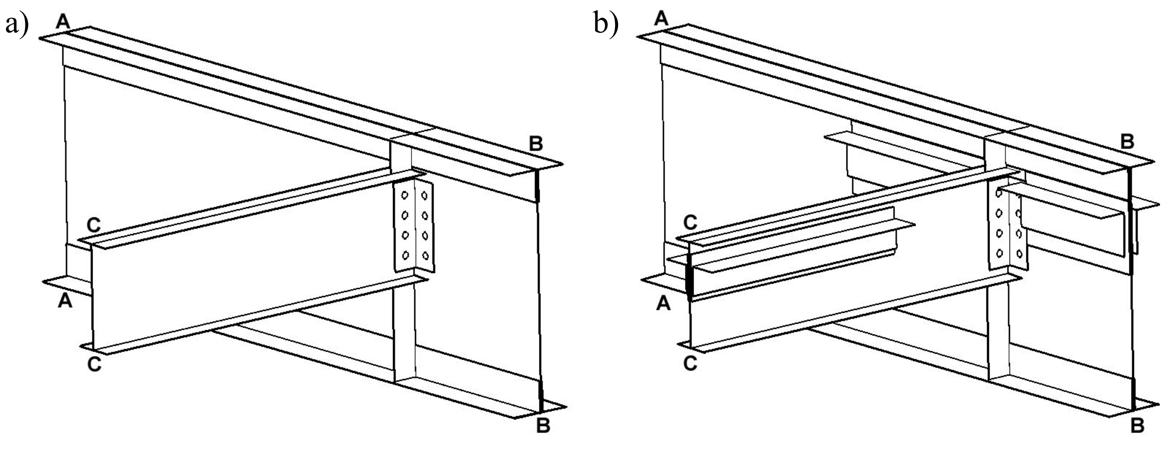

Fig.8. Geometry of FE models: a) "IS" and "CS" (initial stage and current stage), b) "FS" (future stage)

Webs and flanges of connected members and angles were modelled with 3- and 4-node shell elements of 6 degrees of freedom per node (sheet with holes were meshed with triangular and quadrangular elements, others – with rectangular ones). Such modelling proved to be an efficient method of assessing stress distribution in steel connection [5]. In the presented case the FE model was to follow general deformations of members with regard to local deformations of connectors and stress distribution at the C-C section (Fig.8). Thus relatively dense meshing was applied with uniform size of elements. For given boundary parameters mesh was generated automatically.

Rivet modelling is described in detail in chapter 3.1.

Interaction between members was accounted for as frictional contact with friction coefficient μ=0,2.

Model constraints reproduced condition present in symmetry planes at cross-sections B-B and C-C. Cross-section A-A was assumed to be clamped. Model was loaded with concentrated force P=100 kN at the C-C cross-section.

Elastic behaviour of the model and small strain state were assumed.

Three stages of the connection existence were analysed:
– initial stage (“IS”): nominal thicknesses of flanges and webs,
– current stage (“CS”): thicknesses decreased due to corrosion damage as follows: stringer top flange – 15%, crossbeam top flange – 8%, beam webs – 5%, connecting angle legs – 5%,
– future stage (“FS”): as the current stage (“CS”), with strengthening system present.

4 RESULTS OF FEM ANALYSIS

Rotational restraint coefficients were assessed on the basis of two criteria:
– static: rotational restraint coefficient for the stringer (α_s) is expressed by the proportion of restraining bending moment in that member at the actual joint (M_α) to respective bending moment present at the rigid joint (M) [6], as follows:

$$\alpha_s = \frac{M_\alpha}{M} \quad , \tag{2}$$

– kinematic: rotational restraint coefficient for the stringer (α_k) is described by relationship of rotation angle of stringer cross-section at the actual joint (β_α) and pinned joint (β_0):

$$\alpha_k = \frac{\beta_0 - \beta_\alpha}{\beta_0} \quad . \tag{3}$$

Thus α_s=0 or α_k=0 refer to pinned connection while α_s=1 or α_k=1 – to fixed connection.

Results of FEM analyses are summarized in Table 1. Most of symbols used in the table is explained earlier in the text. Other are: $I_{stringer}$ – stringer moment of inertia in bending, M_L – bending moment at the stringer midspan (under concentrated force P). Values of β_0 and M were calculated for the shell-element model of the stringer virtually cut-out from the connection with respect to the stage concerned.

Table 1. Analysis results

Stage	$I_{stringer}$ [m^4]	M_L [kNm]	M_α [kNm]	β_α [deg]	M [kNm]	β_0 [deg]	α_s	α_k
"IS"	19,7e-5	126,1	11,4	0,108	69,2	0,127	0,165	0,150
"CS"	17,8e-5	125,9	11,6	0,117	69,2	0,138	0,168	0,152
"FS"	20,9e-5	128,4	9,1	0,108	66,6	0,118	0,137	0,085

It may be observed that:

– recorded corrosion damage (approximately uniform over stringer and crossbeam) does not alter the initial rotational restraint of stringer-to-crossbeam connection (variation of 2%),

– strengthening of stringer midspan influences midspan bending moment and stringer end rotation in a different way. This is the reason why α_s calculated for "IS" and "FS" drops by 17%, while α_k calculated for the same pair of stages decreases by 43%. Also scatter of α_s and α_k for the "IS" and "CS" is about 9%, while for "FS" it reaches 38%.

5 CONCLUSION

Usually restoring member load bearing capacity means strengthening its critical regions (where the highest stress levels occur). This alters flexural stiffness distribution over member length and influences rotational restraint at its connection to other members. The impact depends on criterion chosen for rotational restraint coefficient assessment. In the analyzed case the strengthening is expected to reduce initial rotational restraint by 17% in terms of restraining bending moment at stringer-to-crossbeam connection and by 43% in terms of stringer rotation at the connection.

REFERENCES

[1] M. Al-Emrani M., R. Klinger, FE Analysis of Stringer-to-Floor-Beam Connections in Riveted Railway Bridges, *Journal of Constructional Steel Research*, **59**, 803-818, 2003

[2] O. S. Bursi, J. P. Jaspart, Calibration of a Finite Element Model for Isolated Bolt End-Plate Steel Connections, *Journal of Constructional Steel Research*, **44**, 252-262, 1997

[3] Agerskov H. High-strength bolted connections subject to prying, *Journal of Structural Engineering Division*, 102(1), 161-175, 1976

[4] ABAQUS/Standard User's Manual, version 6.4, Hibbit, Karlsson and Sorensen, 2003

[5] W. Siekierski, FEM Model of Tested Truss Bridge Joint with Unintended Imperfections, *Archives of Civil Engineering*, **XLVI**, **2**, 337-343, 2000

[6] C.R. Young, K.B. Jackson, The Relative Rigidity of Welded and Riveted Connections, *Journal of Canadian Research*, **11**, 62-134, 1934